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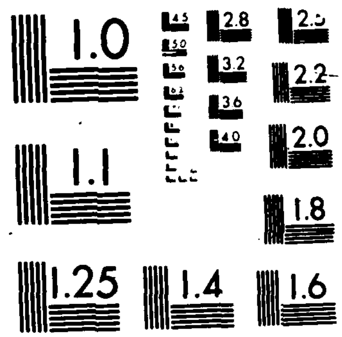
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AN EXPERIMENTAL AND THEORETICAL STUDY OF NUCLEAR-EMP-TYPE LIGHTNING SIMULATORS WITH COMBINED PEAKING CAPACITOR AND CROWBAR

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Experimental and theoretical studies have been carried out to determine the feasibility of combining nuclear electromagnetic-pulse-type lightning simulators which use peaking capacitors with crowbar switches to provide both a double exponential lightning test pulse with a long unipolar tail and a very fast risetime. The purpose of the simulator is to provide a relatively economical and simple lightning simulator for the indirect effects testing of full sized advanced composite aerospace vehicles.

The theoretical analysis and experimental investigations have verified the validity of the concept of combining the peaking capacitor and the crowbar switch to obtain high-current unipolar current waveforms which also have a high current rate of rise with economical components.

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FOREWORD

This report, L&T No. 817, is the final report covering an experimental and theoretical study of nuclear-EM-type lightning simulators with combined peaking capacitor and crowbar.

LTRI personnel participating in this report's studies and preparation included J.D. Robb, B.A. Sventek, T.J. O'Keefe and J.D. Anderson.

The Air Force technical monitor on the contract was Mr. L. Walko of the AFWAL Flight Dynamics Laboratory.

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APPENDIX I - IMPLEMENTATION OF A CROWBAR SWITCH IN A MARX GENERATOR/PEAKING CAPACITOR LIGHTNING SIMULATOR SYSTEM

1.0 INTRODUCTION & SUMMARY

Experimental and theoretical studies have been carried out to determine the feasibility of combining nuclear-electromagnetic-pulse-type lightning simulators which use peaking capacitors with crowbar switches to provide both a double exponential lightning test pulse with a long unipolar tail and a very fast rise time. The purpose of the simulator is to provide a relatively economical and simple lightning simulator for the indirect effects testing of full-sized advanced composite aerospace vehicles.

2.0 BASIC ELEMENTS OF CONCEPT

The new NEMP-type simulator consists essentially of a Marx-type impulse current generator discharging into the aerospace vehicle under test. A coaxial return conductor is used to provide a uniform radial current distribution about the vehicle and a low impedance for high current, as illustrated in Figure 1.

Of particular importance for modern digital circuitry is the current rise time, as the induced voltage and current are determined largely by the current rate of rise. The studies have included a theoretical analysis by Electro Magnetic Applications, Inc. (EMA), Denver, Colorado and an experimental test program by LTRI. The conclusions are presented in the theoretical report presented as Appendix I of this report by EMA and in this report on the experimental study by LTRI.

2.1 Principles of Operation

The basic principle of operation, as illustrated in Figure 1 is as follows. The Marx generator is fired by a trigger switch at the bottom through the Marx series inductance into the peaking capacitor. This results in an oscillation with the total series circuit inductance on the peak of the charge voltage, as the peaking capacitance is only a small fraction of the Marx generator capacitance. At the peak of this voltage, the Marx output spark gap switch fires to provide an initial current determined by the nearly double peaking capacitor voltage and the very low peaking capacitor inductance.

The rise time is determined by the sum of L3 and L4 divided by Z, the series inductance in the peaking circuit and the input inductance to the vehicle total, divided by the surge impedance of the aircraft and return conductor.

The input current to the vehicle reaches a peak value and the crowbar is then fired to change the discharge to a unipolar R-L-type discharge. The early time current is determined by the voltage and the line impedance and the late time current is determined by the resistance of the circuit from the Marx generator through the termination inductance.

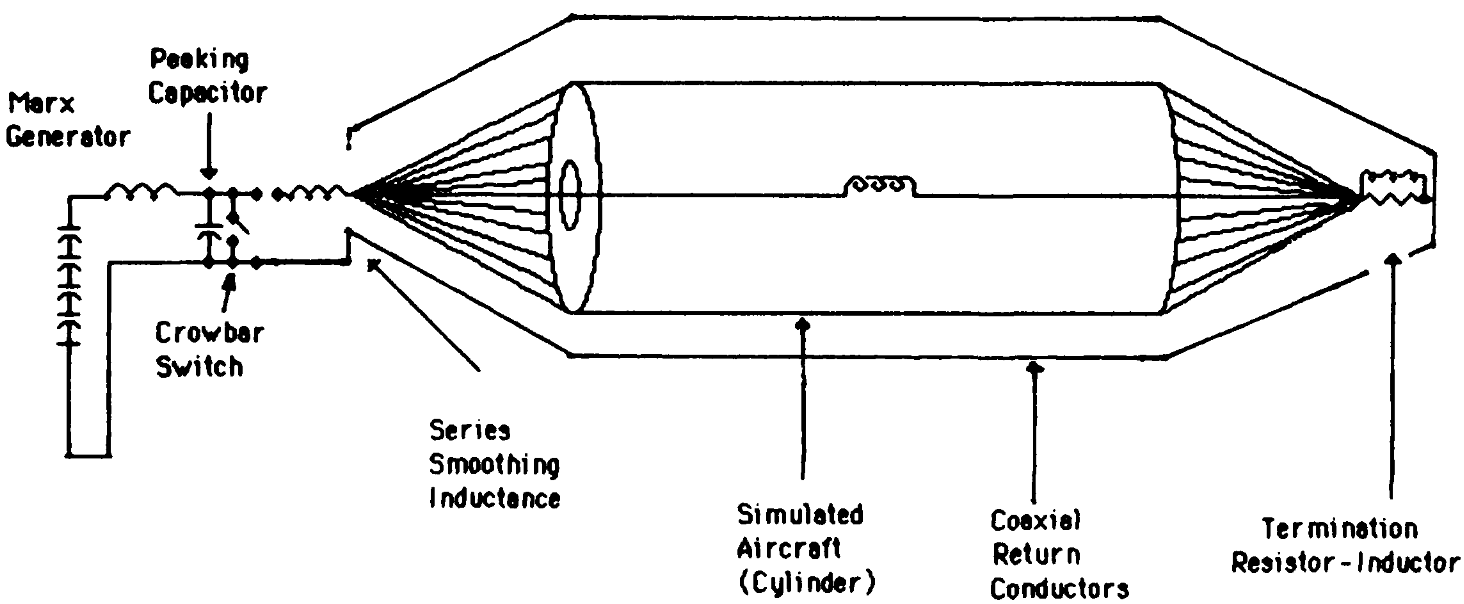

Figure 1. Overall Test Arrangement and Equivalent Circuit for Combined Peaking Capacitor, Crowbar Lightning Simulator

Thus the Marx generator and peaking capacitor see the high impedance required for a fast rise time during the early time phase and see the low impedance of the inductance coil during the late time unipolar phase. This approach provides therefore both the high current and the high current rate of rise.

2.2 Peaking Capacitors

In the earlier study EMA predicted and LTRI demonstrated that a clean fast front of wave could be obtained using a nuclear electromagnetic pulse type peaking capacitor for a fast rise time. By adding some series inductance to slow the front of wave from typical EMP front times of 10 nanoseconds down to typical lightning rise times of 100 to 500 nanoseconds, the front of wave is also much cleaner and this would permit easier analysis of system response data.

2.3 Crowbar Switch

As the peaking capacitor had been demonstrated in the earlier investigations, the emphasis in this program was on the operation of the crowbar switch in conjunction with the NEMP type peaking capacitor. The crowbar switch presents an apparent problem. It is required to provide the long unipolar wave tail which is of importance for testing of all composite graphite structure, but it also lengthens the front of wave time because of the low impedance it presents to the drive system.

This may be explained as follows. The rise time is equal roughly to L/R, the ratio of the load inductance divided by the load resistance as seen by the drive generator. The solution suggested by EMA in their theoretical studies was to use a parallel inductance and resistance for the load. The inductance would provide a high impedance for the fast rising initial current wave but a low impedance load for the slow phases of the high current discharge after the operation of the crowbar and this would result in both a high current peak and a longer tail time.

The experimental studies to date have shown that the basic concepts are valid but that the crowbar switch used in the tests may not be reliable enough for routine use at the high voltage levels of 1.5 to 2 megavolts used for testing full sized aircraft. A new type of crowbar switch has been developed for this application and is proposed for the next phases of the LTRI simulator program to checkout the simple three element crowbar switch at the 1.5 to 2-megavolt level and also to check out the new type LTRI multigap switch.

3.0 EXPERIMENTAL TEST ARRANGEMENT

The experimental test arrangement is shown as noted in Figure 1. It is comprised of (a) the Marx impulse type current drive generator, (b) the NEMP type peaking capacitor, (c) the crowbar switch, (d) the series inductance, (e) the simulated test aircraft (an aluminum cylinder), (f) the return current conductors and (g) the termination resistance/inductance combination.

3.1 Marx Generator

The Marx generator used in the test program had 15 stages of 0.75 microfarad each at a stage voltage of 20 kilovolts, for a total voltage of 300,000 volts as illustrated in Figure 2. A full Marx generator was used to provide the stage oscillations and sparkgap firing hash which would be generated in a full-scale 2-megavolt generator and to evaluate the effectiveness of the series smoothing inductance.

3.2 Peaking Capacitor

The peaking capacitor was initially planned to be made of special low inductance capacitors but calculations showed that inductance would have to be added rather than subtracted in order to increase the rise time to the desired 180 nanoseconds from 20 to 30 nanoseconds. Therefore, standard, more economical energy storage capacitors were used and they provided more than sufficient rise time for the current front of wave. A spiral configuration was used in order to provide a maximum clearance in a minimum space as shown in Figure 3.

3.3 Crowbar Switch

A simple three-electrode switch was selected for the crowbar switch as illustrated in Figure 4. They have the reputation of having excess jitter, but we found that if sufficient voltage and energy are used they can provide reasonable consistency even with relatively low voltage across the switch.

3.4 Series Inductance for Smoothing the Current Front of Wave

The theoretical investigations showed that addition of a small inductance at the input to the simulated aircraft (cylinder) would smooth out the current front of wave which would permit easier analysis of coupling into the circuitry. The inductance for the input to the vehicle for smoothing the front of wave is shown in Figure 5.

3.5 Simulated Aircraft (Closed Aluminum Cylinder)

For simulated aircraft which would permit good correlation between the experimental measurements and the theoretical analysis, an aluminum cylinder 2 meters in diameter and 30-feet long was used. This provided a shielded chamber for location of the measurements oscilloscopes and simulated internal aircraft wiring. The cylinder simulating the aircraft is shown in Figure 6 along with the return grid arrangement.

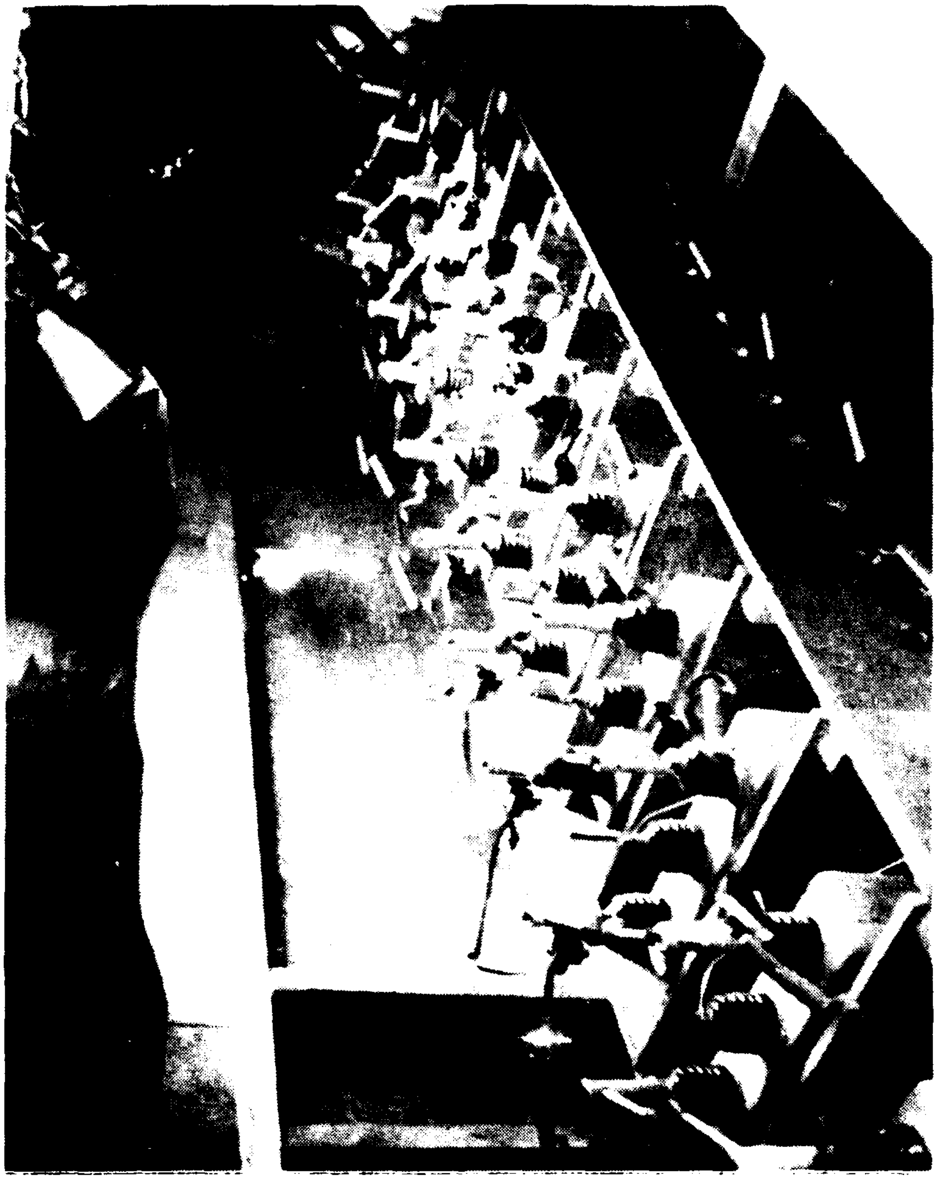

Figure 2. Fifteen Foot, 300-Kilovolt Marx Generator Simulates 2-Megavolt Full-Scale Marx for Simulator

Figure 3. Peaking Capacitors (Standard Energy Storage Capacitors) May Be Seen Faintly under Plastic Sheet in Center of Photo

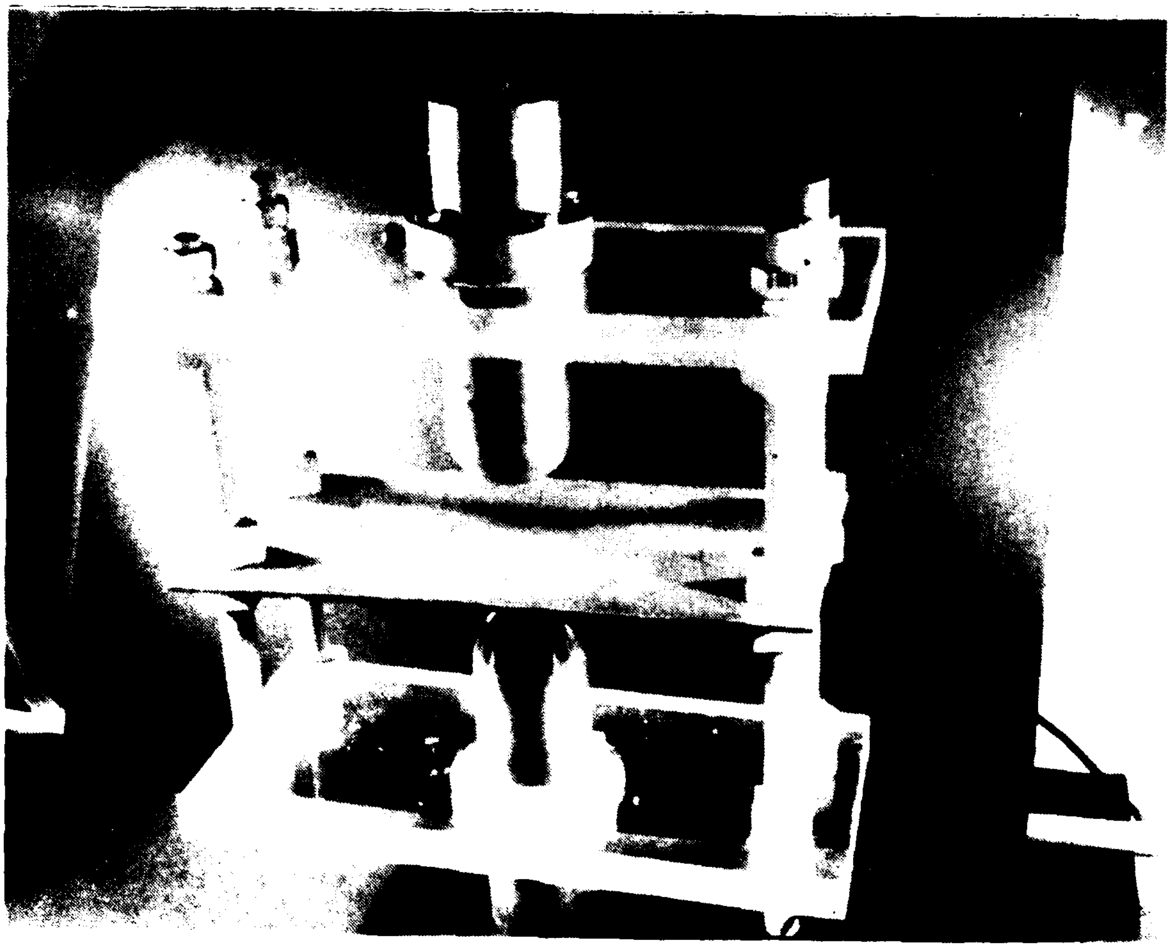

Figure 4. Simple Three-Element Crowbar Switch with Tungsten Inserts Simulates 2-Megavolt SF-6 Filled Unit

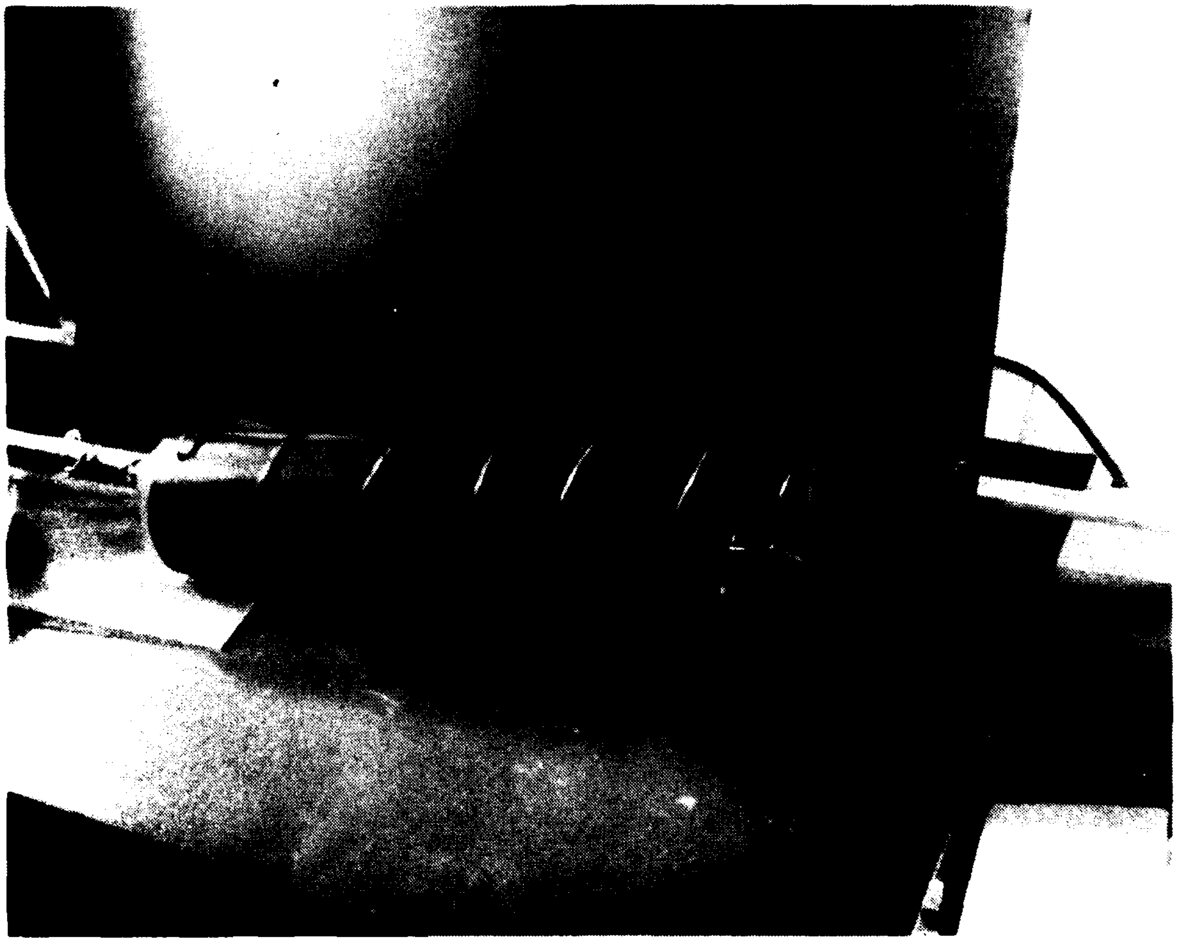

Figure 5. Simple Inductance Coils Used for Three Series Inductance in Marx Output Circuit, Cylinder Input and Termination Inductance

Figure 6. Aluminum Cylinder Simulates Aircraft But Provides Simple Geometry for Correlation with Theoretical Calculations

3.6 Return Current Conductor

A cage of wires was used for the return conductors. Cross connections were made every 2 meters to prevent resonant oscillations on the wires. With the cross connections, the wire grid behaved more like a current sheet at the frequencies of interest in the simulator.

3.7 Termination Resistance/Inductance

Based upon suggestions in the theoretical analysis by EMA, an inductance and resistance were used in parallel for the termination at the end of the cylinder. For the fast current front of wave, the inductance acts as a high impedance and no current flows into it. But the resistance acts as a termination for the transmission line in this initial transmission line phase. After the crowbar switch fires, the slow tail sees the low impedance inductance and provides a large current flow through the simulated aircraft.

Thus, the basic problem of combining a crowbar switch with a peaking capacitor appears to be solved. The fast-time and slow-time characteristics of the combined inductance and resistance provide both the fast rise time and the high current.

4.0 EXPERIMENTAL RESULTS

After delays because of jitter problems in the crowbar switch, tests were carried out which demonstrated the feasibility of the concept. The waveforms were not as clean as had been hoped for, but were sufficient for the purpose of aircraft testing. The important thing is that the approach permits the development of high currents and high current rates of rise with economical equipment available to any major test laboratory. The Marx impulse generators can be modified to high rate of rise with the peaking capacitor, and the high currents and action integrals can be obtained with the combined resistance and inductance for the line termination.

5.0 CONCLUSIONS

The theoretical analysis and experimental investigations have verified the validity of the concept of combining the peaking capacitor and the crowbar switch to obtain high current unipolar current waveforms which also have a high current rate-of-rise with economical components.

6.0 RECOMMENDATIONS

For this program a simple three-electrode switch was used for demonstrating the concept. A new multielectrode switch is under development by LTRI, and this is suggested for more effective crowbar action with less loading and more reliable operation. Also, based on the flight research programs, which indicate the existence of much fast low-level "E" field activity, exploration of the concept of incorporating a downstream gap to

excite the system in this mode is also suggested. The attempts to obtain a smooth front of wave and the higher frequency excitation appear to be in conflict but are not necessarily so. The concept of setting the level of the front gap shock excitation by adjusting the input inductance to the aircraft so that the high-frequency excitation and the front of wave level are to scale is suggested. The concept of also incorporating the downstream gap into this system should also be investigated even though the system begins to be complicated with this addition.

With whatever system is finally selected, we strongly feel that if full-scale aircraft tests are to be carried out, a single combined generator should be used to limit the full-sized indirect tests to a single test sequence with one lightning simulator because of the time required to change connections when monitoring the many circuits in a modern aircraft. To have to make these connections twice for two simulators requires excessive test time for the developmental aircraft, which have a low availability.

APPENDIX I

IMPLEMENTATION OF A CROWBAR SWITCH IN A
MARX GENERATOR/PEAKING CAPACITOR LIGHTNING
SIMULATOR SYSTEM

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CHAPTER 1

INTRODUCTION

The electromagnetic interaction of lightning with aircraft has received an increasing amount of interest in recent years for several reasons. The first reason has to do with the knowledge of the environment. Recent studies have shown that the frequency content of lightning waveforms has significant amplitude in the aircraft resonance region, which is in sharp contrast to previous understanding of the lightning environment.

A second set of reasons has to do with aircraft technology. New and existing aircraft are being made out of advanced composite materials because of their advantageous strength to weight ratios when compared with metals. A third reason is that modern aircraft are being equipped with low-level semiconductor circuitry which have critical roles in functions such as stores management and fly-by-wire systems. Therefore, a great concern arises for preventing upset of these critical digital systems.

Because of these reasons, it is necessary to develop techniques which can be used to test aircraft with an appropriate lightning environment.

An approach based on the use of a Marx generator with a peaking capacitor has previously been reported [1-5]. This approach makes it possible to inject a current with a rate of rise exceeding 2×10^{11} A/s into a full scale fighter size aircraft, and with a peak current level on the order of 40 kA.

One of the problems of the above approach is that the late time waveform is a damped sinusoid whose ringing frequency is determined by the Marx generator capacitance and the combined inductance of the Marx plus the aircraft under test. The frequency of oscillations is too high to permit experimental investigations into redistribution times of current on mixed metal composite aircraft, and other late time effects.

This limitation can be overcome by shorting out the Marx generator when the energy in the aircraft is close to the maximum. The decay will then be exponential, because the Marx capacitance is no longer part of the circuit. This shorting of the Marx is accomplished by a "crowbar" switch, which physically consists of a triggered gap which turns on at a predetermined time. The late time currents are therefore sufficiently long to investigate coupling effects regarding carbon fiber composite (CFC) aircraft.

In this paper, numerical modeling results are presented which indicate the usefulness of the crowbar switch approach. First, the approach is applied to a uniform cylindrical test object, in order to study responses which are not confused by the presence of variations in a real aircraft geometry. Next, the approach is applied to a three dimensional (3D) model of an F-16 aircraft.

The analysis shows that the crowbar switch can be used to accomplish the desired objectives. The test approach does introduce spurious resonances from the test fixture/aircraft interaction. An approach is also given for terminating the aircraft such that these resonances are minimized. It is found that the approach works quite well for a uniform cylinder, but is not as effective for a real aircraft geometry.

CHAPTER 2

RESPONSE OF A UNIFORM CYLINDRICAL TEST OBJECT

A right circular cylinder test bed is used to provide basic information for the response of an object in a candidate simulator design configuration. The basic cylinder configuration is shown in Figure 2.1, which includes the Marx generator, geometrical information, spark gaps, and terminations. This response is obtained by treating the configuration as a uniform transmission line.

The model combines the solutions for the telegrapher's equations in the test fixture itself with the solutions for the circuit which represents the Marx generator. The solution is accomplished in the time domain using finite difference techniques [6].

The results for the injected current, I, are shown in Figures 2.2 and 2.3.

In Figure 2.2, the responses with and without a crowbar are indicated for a short circuited termination ($R_T = 0$). When there is no crowbar, 3 resonances are indicated:

1. The 1.45 kHz oscillation due to the resonance of the Marx generator with the test object.

2. The 1.5 MHz oscillation due to the resonance of the peaking capacitor with the test object.

3. The 6.7 MHz oscillation of the test object shorted on one end and loaded in a 2.5 nf capacitor on the other.

The crowbar is switched on at the time of the largest peak current. It is clear that the crowbar eliminates the lowest frequency oscillation.

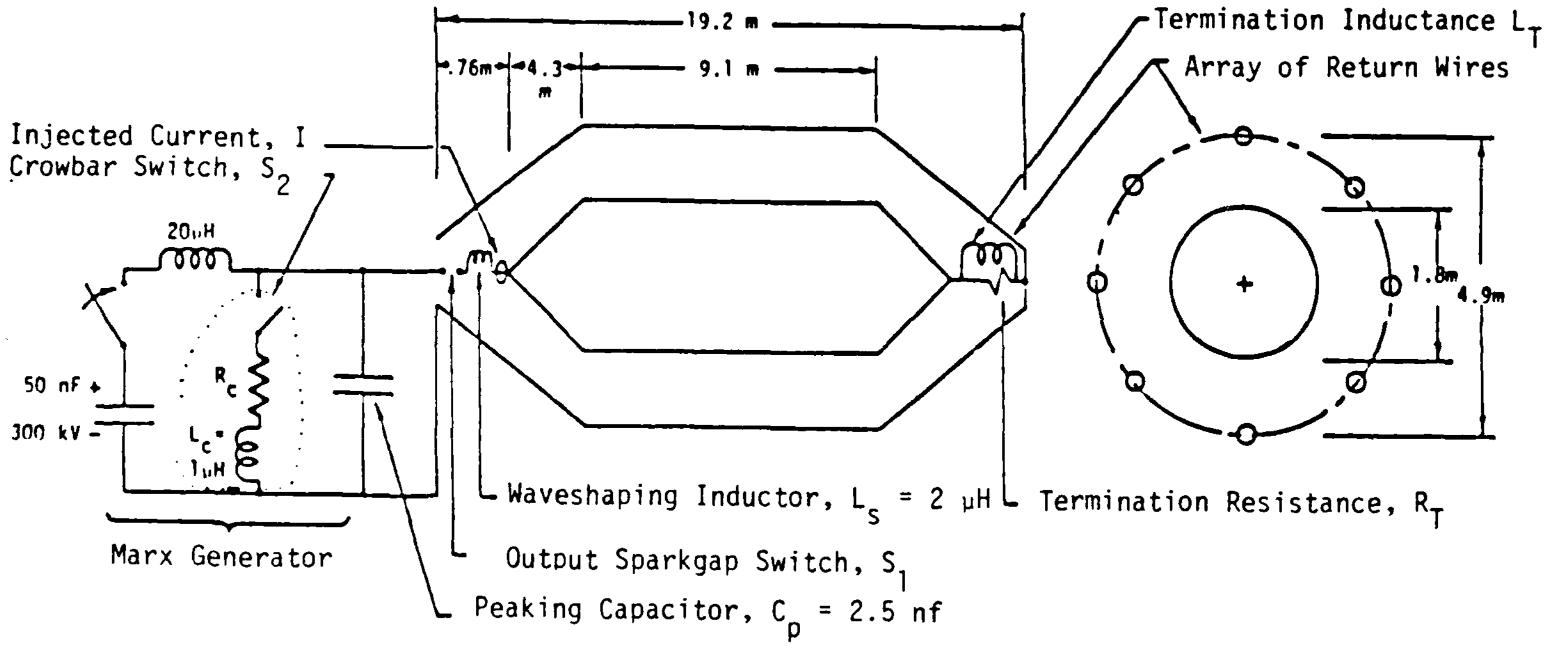

Figure 2.1 Basic Cylinder Configuration. S_1 Turns On When the C_p Voltage Reaches 300 kV

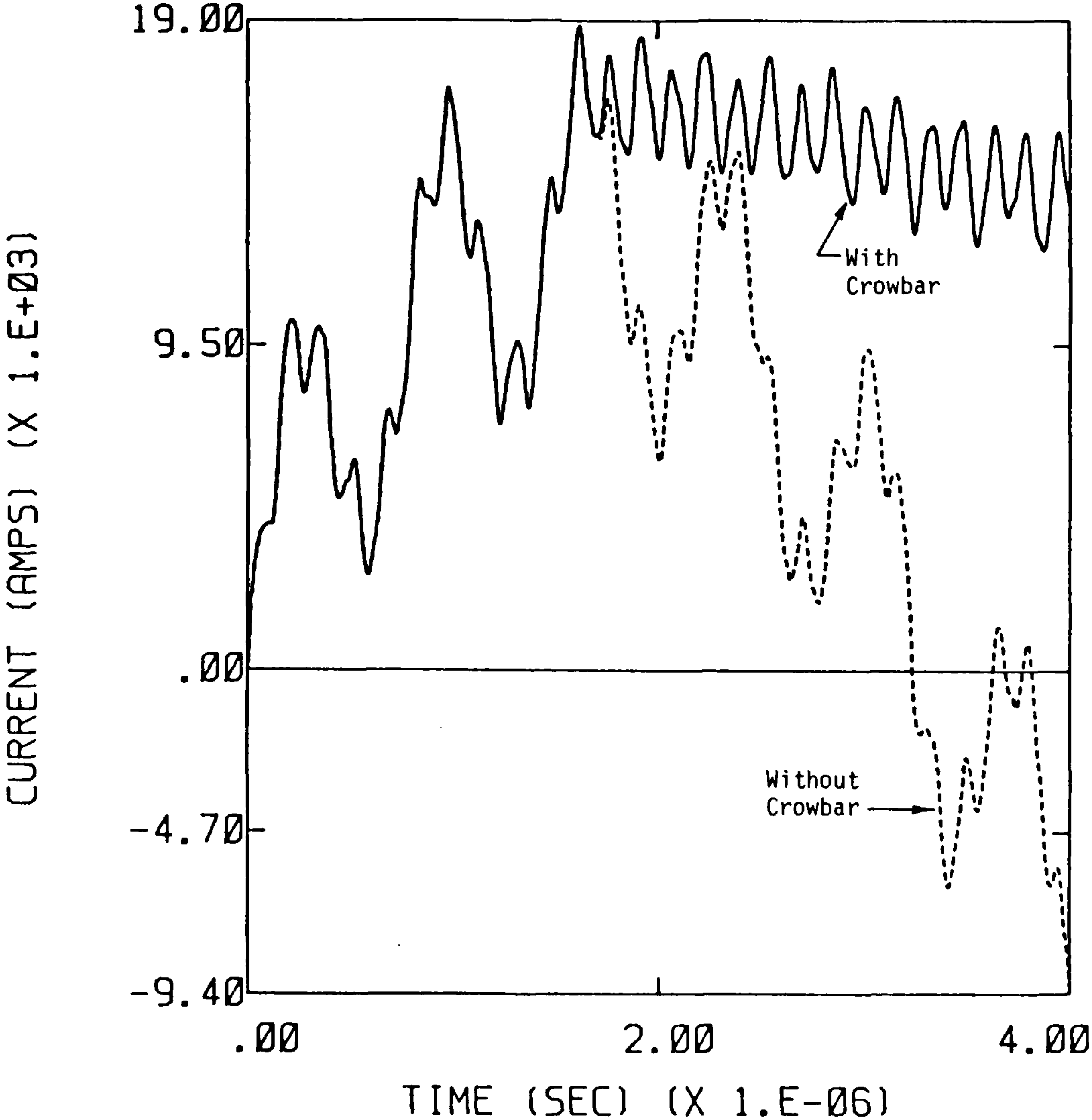

Figure 2.2 Current I for a Shorted Termination, With and Without a Crowbar Switch

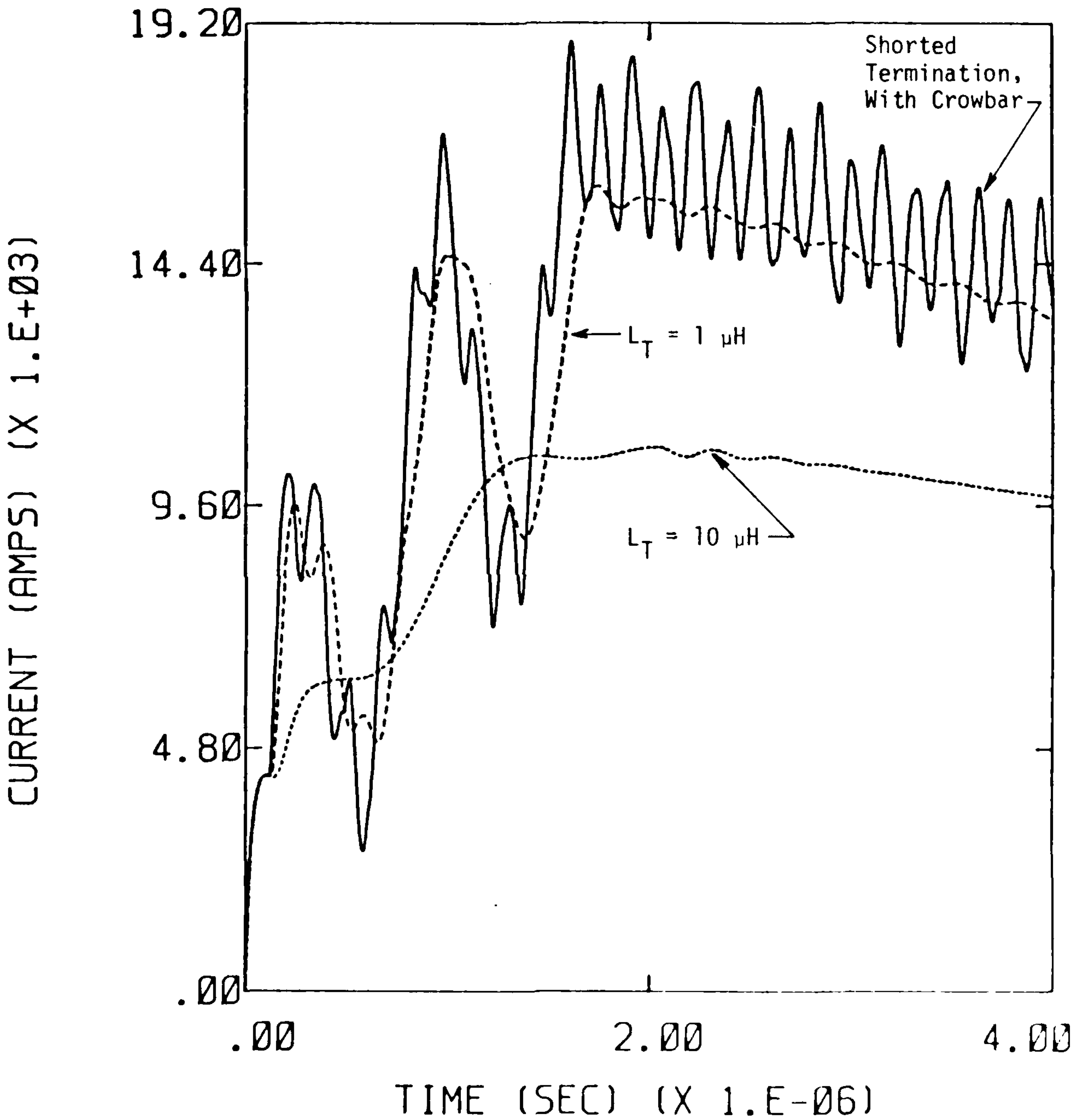

Figure 2.3 Current I with R_T = 71.4 and L_T = 1 μH and L_T = 10 μH, Both With a Crowbar. Results for Shorted Termination With Crowbar Also Shown For Comparison.

The other oscillations are troublesome because they, too, are caused by simulator/test object interactions. One approach to minimize these resonances is to provide a matched termination impedance (71.4Ω) on the transmission line. The disadvantage of this approach is that the peak current level will be limited to approximately 4 kA (300 kV divided by 71.4Ω). An alternate approach is to put a shunt termination inductance L_T in parallel with the resistance R_T. The objective in doing this is that at high frequencies, the line is nearly perfectly matched, but at low frequencies, the termination is inductive. Thus the high frequency oscillations are heavily damped, and the low frequency current discharge of the Marx generator is limited by the termination inductance and not the termination resistance.

Results for L_T = 1 or 10 μH are shown in Figure 2.3. A 1 μH inductance allows the highest frequency resonances to be damped fairly well, but the lower frequency resonances are not. A 10 μH inductance will significantly damp even the lower frequencies. The price that is paid for damping the oscillations is reduction of the injected current amplitude. However, even with 10 μH, the peak current is nearly 11 kA, significantly higher than the 4 kA one could obtain with a matched resistive termination.

One other approach which could be done would be to switch the crowbar at the earliest main peak. Although no analysis of this case was done, it is clear from Figure 2.3 that the peak current would be about 9 kA for 1 μH inductance, but only about 6 kA for the 10 μH inductance. The late time response would be a damped exponential with superimposed high frequencies of about the same amplitude as indicated in Figure 2.3.

The results show that the crowbar switch can be used to provide the desired late time response.

CHAPTER 3

THREE DIMENSIONAL AIRCRAFT RESPONSE IN A FULL SCALE SIMULATOR

The modeling approach is the same as in the previous study [1,2], but is repeated here for convenience.

The three dimensional finite difference technique [6] is used to model the response of a full size aircraft in a full scale simulator. The configuration is shown in Figure 3.1. The large clearances are required to provide sufficient voltage stand off such that arcing of the aircraft to the fixture does not occur. Voltages exceeding 6 MV are expected on the aircraft.

The aircraft is an F-16, and the shape of the computer model is shown in Figure 3.2. The cell size is 1 meter in the longitudinal direction, and is 1/2 meter in the other directions. The time step is 1 ns. Because approximately 5 cells are required to resolve a wavelength, the upper frequency limit of the computation is 60 MHz. The erected Marx voltage is 4 MV, and the output spark gap is adjusted to arc over when the gap voltage exceeds 6 MV. The measurement point is the injected current I.

The results are shown in Figures 3.3 - 3.5.

Figure 3.3 shows the injected current for a shorted termination with and without a crowbar. The effect of the crowbar is clearly seen and extends the current out in time. There is a resonant structure on the waveform due to the natural resonances of the aircraft in the test fixture and the interaction of the aircraft with the test configuration. They may be summarized as follows:

1. The 4 MHz resonance is the resonance of the aircraft shorted to the fixture on one end and terminated in the peaking capacitance on the other end. This is roughly a quarter wave resonance.

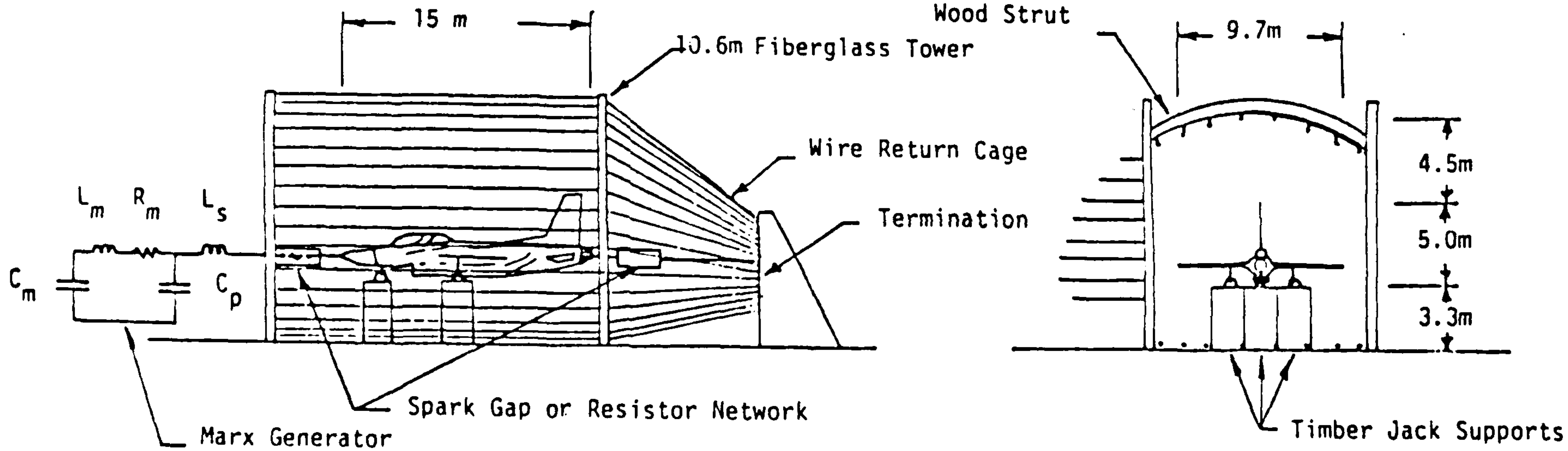

Figure 3.1 F-16 Aircraft in Full Scale Simulator

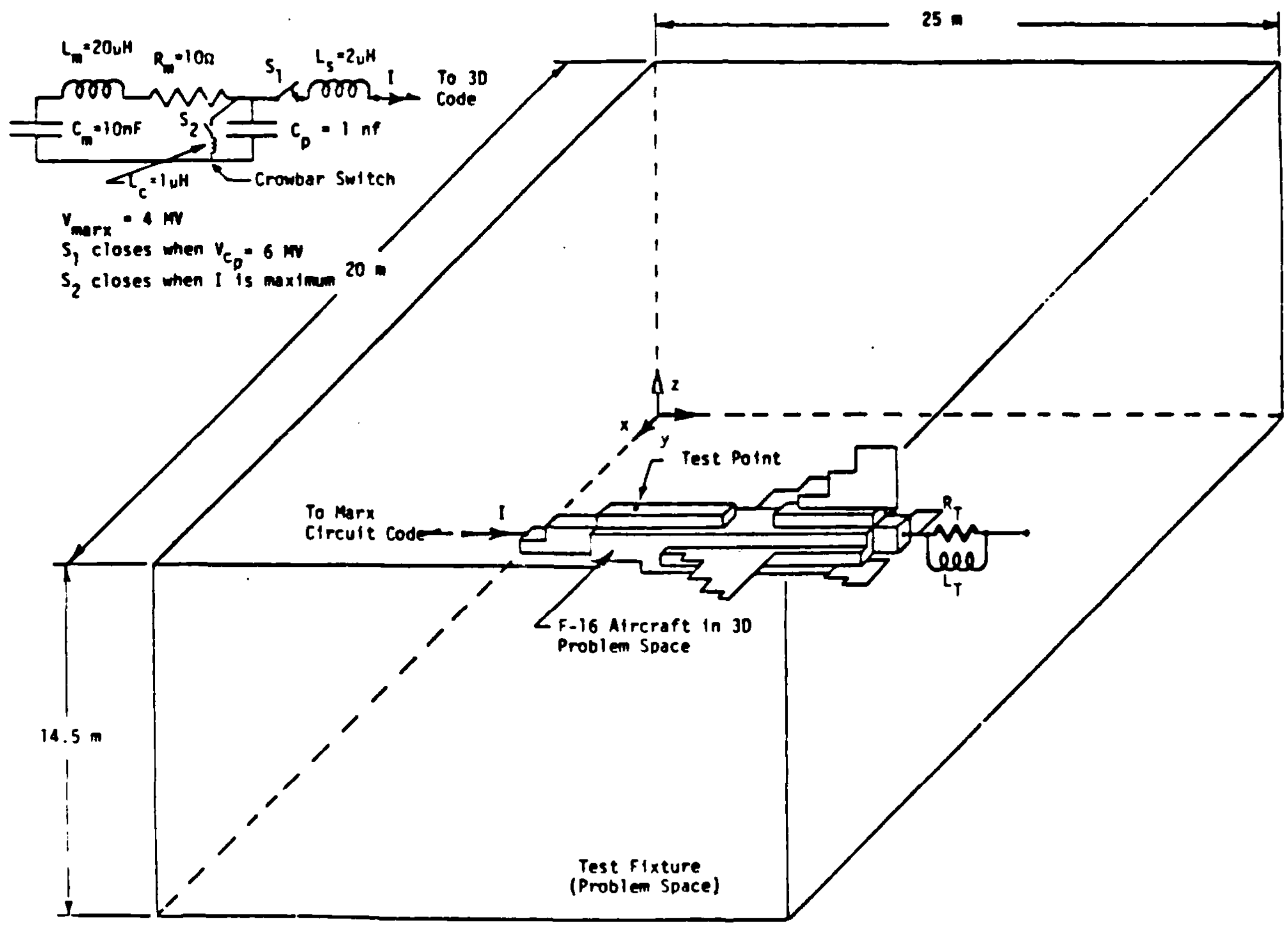

Figure 3.2 Three Dimensional Finite Difference Model of F-16 Aircraft in Text Fixture

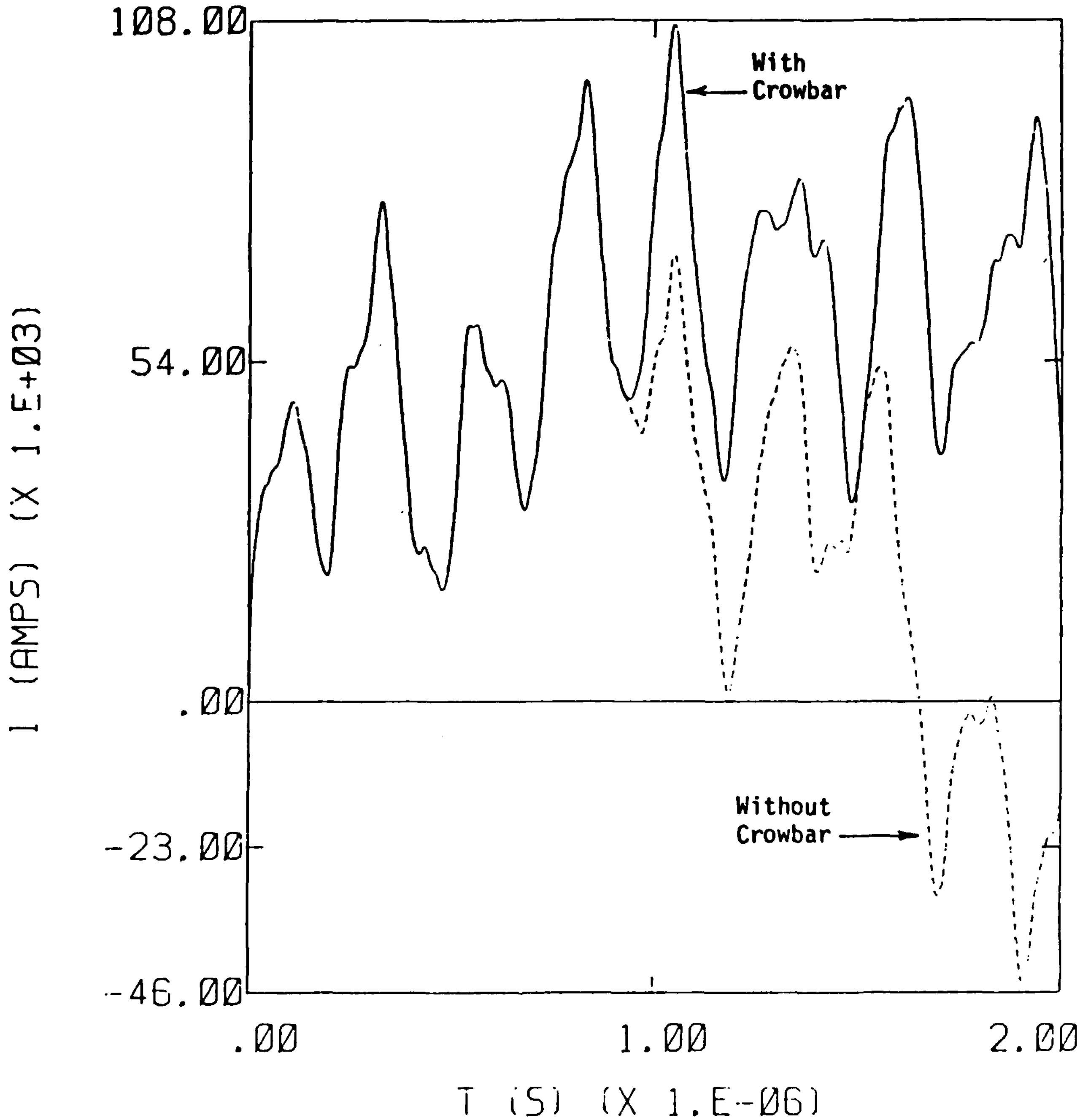

Figure 3.3 I for Short Circuited Termination With and Without a Crowbar.

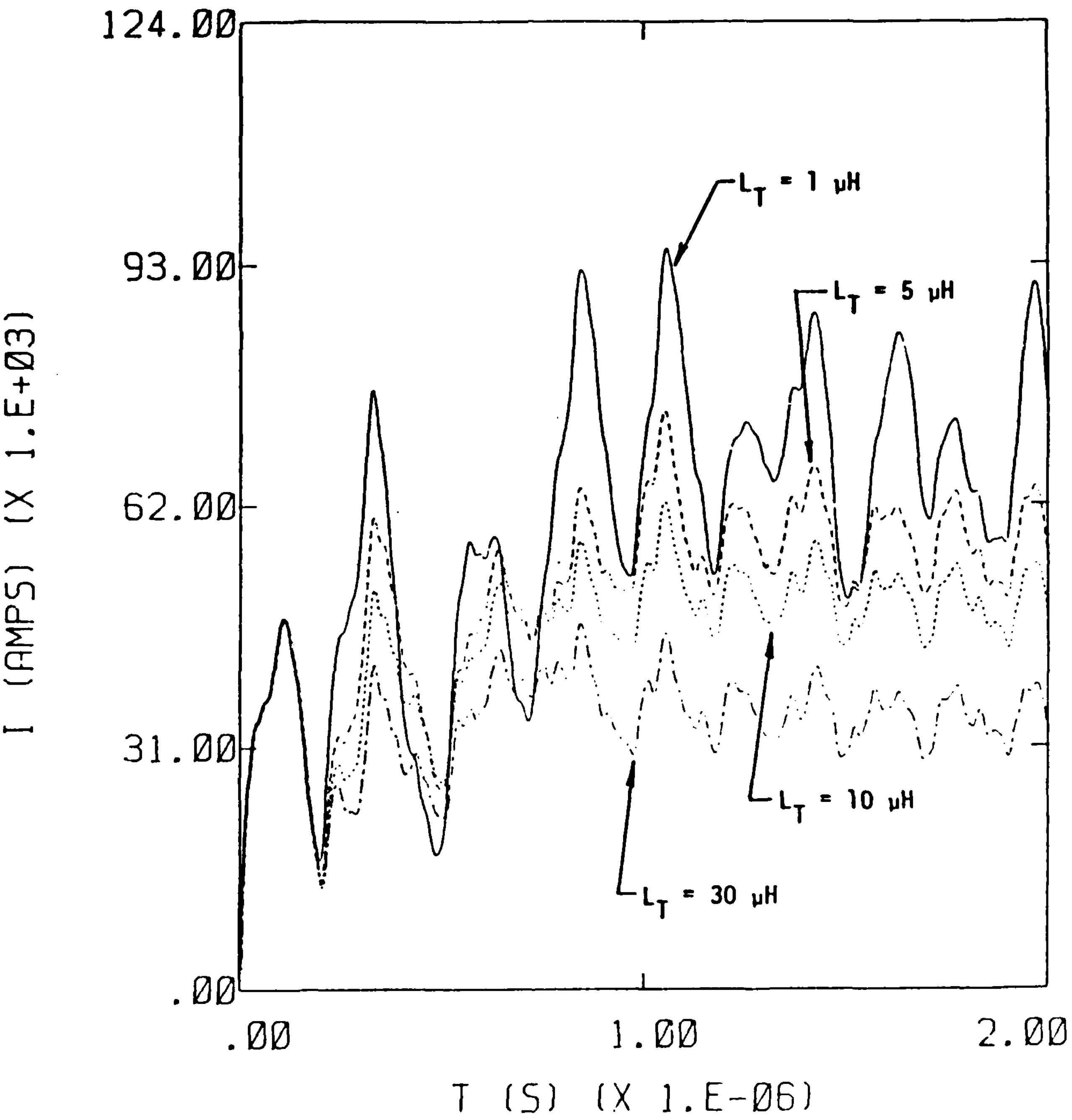

Figure 3.4 I with 78 Ω Termination and Different Values of the Shunt Inductance.

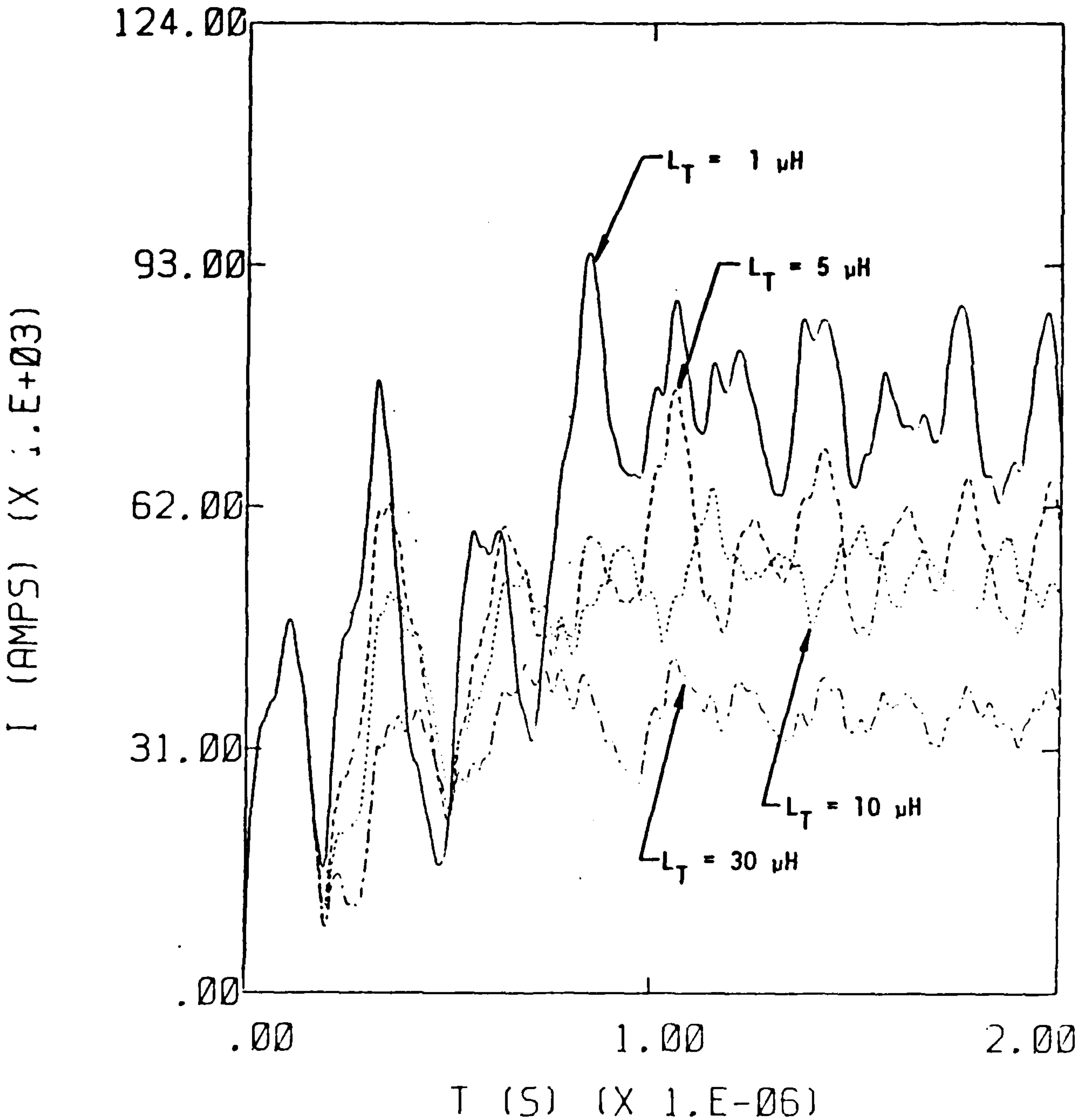

Figure 3.5 I with 150 Ω Termination and Different Values of the Shunt Inductance.

2. The roughly 250 kHz resonance of the Marx capacitor discharging into the aircraft and Marx inductances.

3. Higher frequency resonances on the order of 10 MHz which are related to aircraft structure dimensions.

It is desirable to damp out the aircraft/test fixture resonances, in the same manner as was described in Chapter 2. Figure 3.4 shows the injected current for different values of L_T and with $R_T = 78\Omega$. Figure 3.5 shows the same thing for $R_T = 150\Omega$. The 78Ω case seems to be a better match, but the match is not very good in any case. The spurious oscillations are not greatly damped in any case, although the 30 μH inductance with 78Ω seems to be the best. The damping is not nearly as good as was possible with the cylindrical geometry previously discussed. This is because the aircraft is not a uniform transmission line, and the aircraft impedance seen at the termination is a frequency dependent complex number, and cannot be completely damped with a resistor, as is possible with a uniform transmission line.

CHAPTER 4

SUMMARY AND CONCLUSIONS

The intent of the work reported here has chiefly been to demonstrate the applicability of a crowbar switch to a fast risetime simulator configuration. The results indicate that the approach can be successfully used to increase the pulse width beyond the time constants of interest for testing composite aircraft.

A separate but related issue concerns the presence of resonances in the injected current which are caused by interaction of the test object with the simulator. An approach was studied to minimize these resonances. It was found that for a uniform transmission line, they could be damped by terminating the line in its characteristic impedance, and shunting this with an inductor which still allows a rather large late time current. When applied to an actual aircraft, this approach does reduce these resonances, but not to the same degree as was possible with a uniform line. This is because the aircraft geometry cannot really be represented by a uniform transmission line. However, it is believed that these spurious resonances might be reduced with more judicious choices for termination impedances and a more detailed test fixture design.

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